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Wind Power Cost and Value Analysis of China

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Wind Power Cost and Value Analysis of China

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Abstract

Wind Power Cost and Value Analysis in China

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The University of Texas at Austin, 2017

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With the development of society and industry, demand for energy is growing. The environmental issues caused by mining, transportation and consuming of conventional fuels are associated with these risks. Wind energy, as a strong power on earth, has been developed for decades. With much attention drawn to it and the development of technology, the cost of wind power has been reduced to a relatively competitive price. Thus the utilization of wind power has been widely obtained globally. However, the cost of wind power is still too high to compete with conventional thermal power if without incentives. As a result, it is important to find influential factors to this problem. This research paper presents the costs and potential of wind power and measures for identifing cost.

This paper analyses wind power cost, which mainly consists of three part: investment cost, operation and maintenance cost and financial cost. Site selection, wind energy source, turbine selection method along with tax policies are also discussed here. And then a mathematical model is derived, which allows an analysis wind power cost.

This paper also discusses the integration cost and environmental risk. The randomness of wind resource and the uneven distribution of electricity supply and demand

lay heavy burdens on electricity management: wind energy is better with additional reserve capacity and energy storage. Also wind power generation help reduce damages from coal production, transportation and use. Cost spent on grid integration caused by the uncertainty of wind energy should also be considered.

Based on an integrated model, this report analyzes factors influencing wind power cost. A 50MW wind farm is assumed to be built in Urumqi area. It’s cost along with its environmental value is calculated using the method discussed in this report. And the result is compared with wind power price and coal piece.

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Chapter 1: *Introduction*

THE ENERGY STRUCTURE IN CHINA

Energy consumption has increased rapidly subsequent to P. R. China's becoming a member of World Trade Organization. Coal has been the dominant energy source in China for decades. In 2010, coal accounts for around 70% while oil accounts for 15% of all the energy consumption [1] illustrated in figure 1. It also illustrates that there is increasing consumption of natural gas, along with hydro and other renewables. Although renewable energy use is still insignificant compared to other energy sources, it is developing fast.

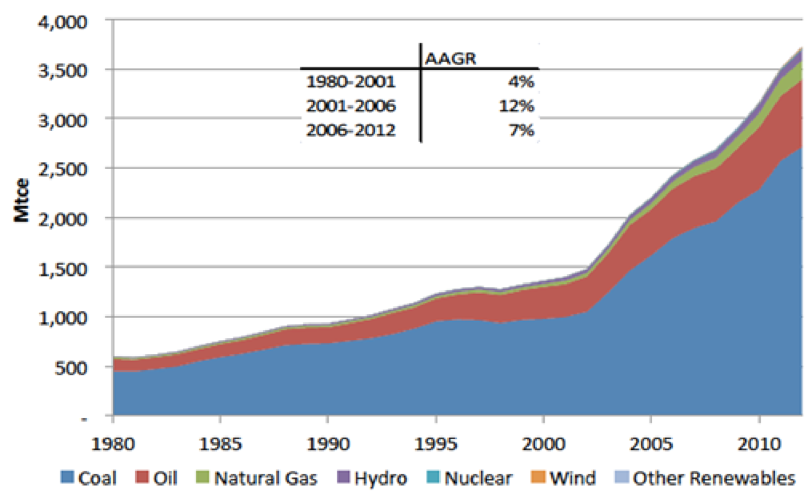


Figure 1: China's Total Primary Energy Consumption by Source (1980-2012).

Source: Leung, G.C.K. et al., 2014. Securitization of energy supply chains in China. Applied Energy, 123, pp.316–326.

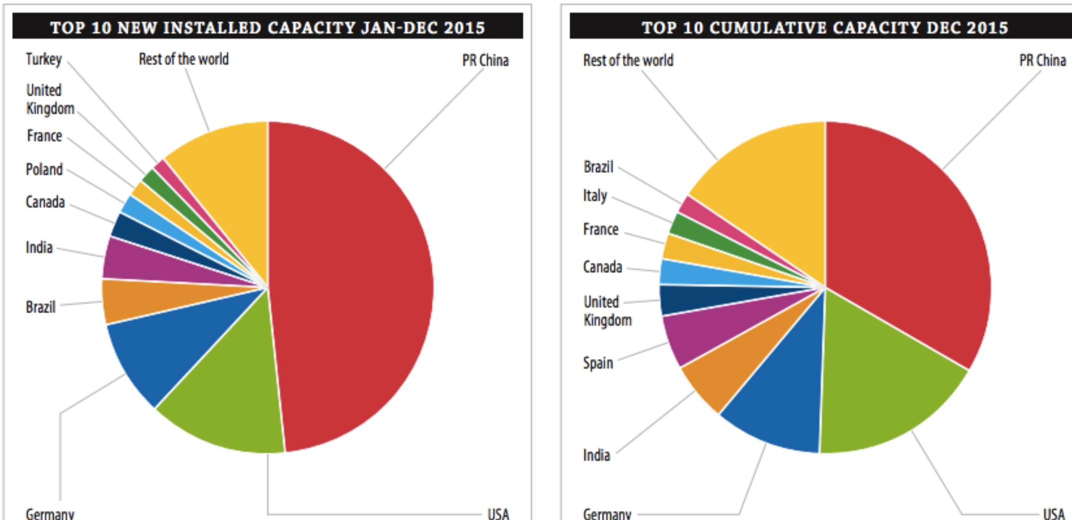
Fossil fuels have caused serious environmental issues in China. Mining, transportation and use of fossil fuels can harm the environment. Coal mining not only affect workers' health, but soil, vegetation and terrain are also damaged. Its combustion produces pollutants to air and water. One report suggests that every 10 thousand tons of coal is mined, there will be 0.2-hectare surface subsidence [2]. During coal combustion, pollutions like sulfur dioxide, nitrogen oxides, carbon dioxide, carbon monoxide and particulate dust are emitted. Carbon dioxide produced by fossil fuels aggravate global warming. Sulfur oxide can be a precursor for acid rain. Nitrogen oxide and metal elements can affect the health of plants, animals and human. As a result, renewable energy should play a more important role in energy consumption.

WIND POWER DEVELOPMENT

Wind power is the use of air flow through wind turbines to mechanically power generators for electric power. Wind power, as an alternative to burning fossil fuels, is plentiful, renewable and relatively clean, because it produces no pollutants and greenhouse gas emissions during operation. It also consumes no water, and uses little land [3]. Modern wind turbines are much larger in size and more reliable than the 1970s-1980s versions. The power rating of wind turbines has increased from just a few kilowatts to 1-3 MW for a single unit in 2012 [4].

In 2015, annual global wind power installations reached 63 GW of new capacity and the total wind power installations reached 432.9 GW, representing cumulative market growth of more than 17% compared to 2014. For example, in 2015 wind power contributed a new installation figure of 30,753 MW in China for a total 145.1 GW installed capacity. In 2015, the electricity generated by wind power was 186.3 TWh in China, representing 3.3% of total national electricity consumption [5].

As of 2015 China has the largest volume of installed wind capacity at 33.6%. United States accounts for 17.2% of cumulative capacities with Germany 10.4% of the share. India, Spain, United Kingdom, Canada, France, Italy and Brazil are the rest of the top 10 countries. According to U.S. Energy Information Administration, the predicted global installed capacity of wind power would be 506 GW in 2020. China is forecast to have 250 GW of wind capacity as part of the government's pledge to produce 15% of all electricity from renewable resources in this year [6].



Country	MW	% Share
PR China	30,753	48.5
USA	8,598	13.5
Germany	6,013	9.5
Brazil	2,754	4.3
India	2,623	4.1
Canada	1,506	2.4
Poland	1,266	2.0
France	1,073	1.7
United Kingdom	975	1.5
Turkey	956	1.5
Rest of the world	6,950	11.0
Total TOP 10	**56,517**	**89**
World Total	**63,467**	**100**

Source: GWEC

Country	MW	% Share
PR China	145,362	33.6
USA	74,471	17.2
Germany	44,947	10.4
India	25,088	5.8
Spain	23,025	5.3
United Kingdom	13,603	3.1
Canada	11,205	2.6
France	10,358	2.4
Italy	8,958	2.1
Brazil	8,715	2.0
Rest of the world	67,151	15.5
Total TOP 10	**365,731**	**84.5**
World Total	**432,883**	**100**

Source: GWEC

Figure 2: Top 10 New Installed Capacity and Cumulative Capacity in 2015

Source: U.S. Energy Information Administration. 2016. International energy outlook 2016. Washington D.C. USA.

With its large mass and long coastline, China has exceptional wind power resources. Figure 3 [7][8] illustrates wind power capacity and electricity production from 2005 to 2015. China's wind power industry has increased rapidly each year.

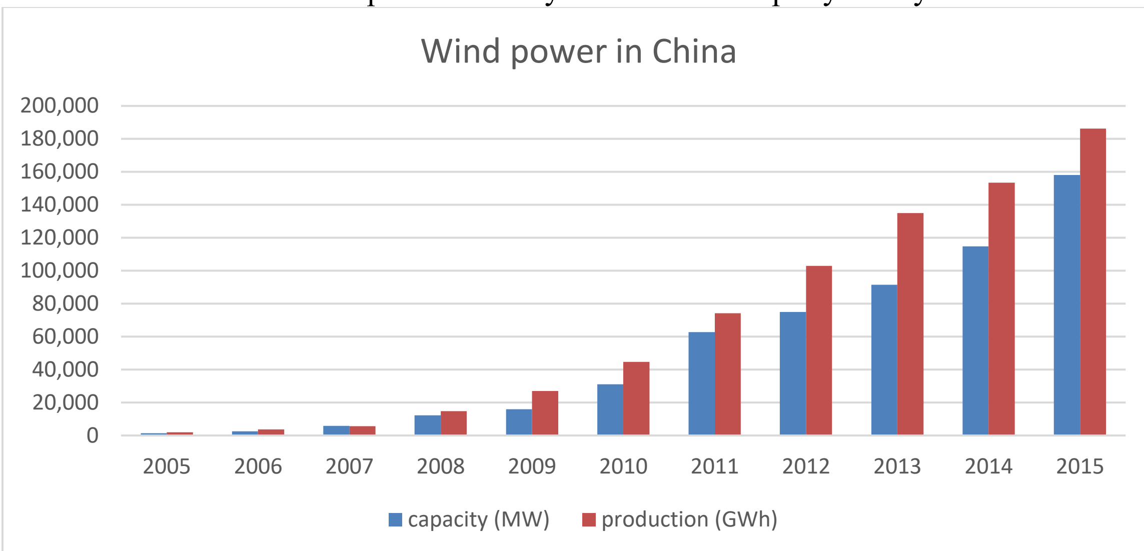


Figure 3: Installed Capacity of Wind Power and Its Electricity Production in China

Source: Energy Information Administration. 2013. Wind Electricity Installed Capacity. International Energy Statistics. Washington D.C., USA. Energy Information Administration. 2013. Wind Electricity Net Generation. International Energy Statistics. Washington D.C., USA.

Although China has the largest installed wind capacity, the percentages of wind power electricity generation to the total electricity production in many European countries are higher than in China. For example, Denmark generated 42.1% of its electricity by wind. One of the reason causing this is wind curtailment. That results from local incapability of grid integration, mismatching of wind farm constructing period and the high wind power cost .In China, 21% of wind turbines are curtailed in the first half year of 2015 [9].

WIND POWER COST

In places where there is good wind resource and conventional thermal power has high marginal cost, onshore wind power can compete with conventional power. In Brazil, the bidding price for wind is as low as 1.9 cent/kWh. [[10]] Onshore wind power cost has been approaching newly-built coal fire plant or natural gas fire plant in Australia, Chile, Mexico, New Zealand, Turkey and South Africa, However, from a global perspective, the cost per kWh of wind power is still higher than conventional electricity resources in many nations and regions.

For China, the onshore wind power in 2013 cost lies between 0.35 yuan/kWh and 0.5 yuan/kWh. The corresponding wind feed-in tariff level is set at 0.51 yuan/kWh to 0.61 yuan/kWh. Without considering the environmental benefits, wind power's costs and tariffs are higher than for coal-generated thermal power.

Investment cost

In 2013, the investment cost of onshore wind power is about $1100/kW in China. In United States and Europe, the capital investment costs ranges from $1600/kW to $21700/kW [[11]]. During 2004 to 2009, the investment cost of onshore wind power increased greatly. The main reason is the shortage of wind turbines and their supply parts, and the increase in steel and copper price. Since 2009, the investment cost decreased remarkably, due to competition among wind turbine producers. During 2008 to 2013, the per kilowatt investment cost of global wind power fell at least a third [[12]]. Figure 4 illustrates that wind turbine costs between 2004 and 2012.

The installed cost of a wind power project is dominated by the upfront capital cost, also known as capital expenditure. Capital cost can be as much as 84% of the total installed cost. The cost of offshore wind power is about 2 to 3 times onshore wind power. For offshore wind, wind turbine cost accounts for less than 50% of total cost. The turbine cost of onshore wind power project accounts for 70% to 80% of total cost [[13]].

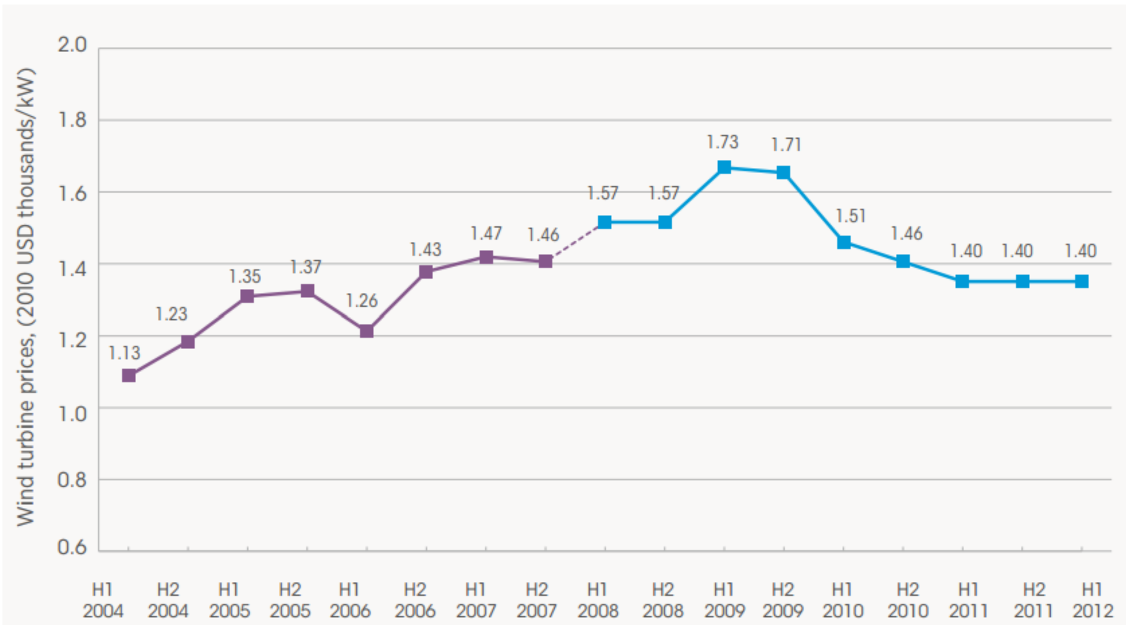


Figure 4: Wind Turbine Price Index by Delivery Date from 2004 to 2012

Source: BENF. 2011. Levlised Cost of Energy Update, Q2 2011, Research Note, BNEF, February, London.

Operation and Maintenance Cost

O&M cost accounts for 15% to 25% of the total cost, including maintenance, spare parts, insurance, management and rent. According to statistics, O&M cost decreased about 44% from 2009 to 2013. Under a circumstance that the capacity factor is 25%, the operation and maintenance cost can be as low as 1 cent/kWh in United States in 2013 [[14]]. The overall O&M cost of offshore wind power ranges from 2.7 cent/kWh to 5.4 cent/kWh [[15]]. Figure 5 illustrate the operation and maintenance cost in Europe between 2009 and 2013.

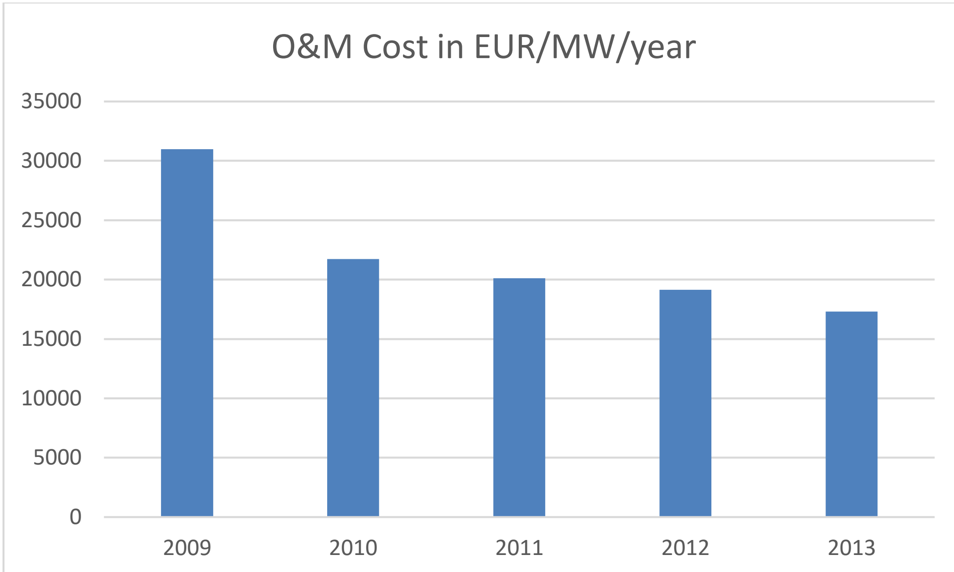


Figure 5: O&M Costs for Wind Power Projects in the Europe from 2009 to 2013

Source: Tabbush, E. 2013 Operations and Maintenance Price Index, Issue II, Wind – Research Note, BNEF, 4 April.

Unit Cost

The cost per kilowatt hour is related to wind resource, investment cost, operation expense and maintenance expense, the cost of finance and any increase in the capacity factor caused by technology improvement. Higher tower and longer blade diameter can catch more energy. Offshore wind can be stronger than onshore wind, so a single wind turbine can generate 50% more power offshore than onshore. Currently, offshore wind power costs around 16.2 cent/kWh while onshore wind power cost is around 5 cent/kWh [19]. Offshore wind farm costs more than onshore wind farm because the farther the project is from shore, and the deeper is sea, then the higher the cost of fixing a wind turbine to the sea bed, as well as integrating the turbine to the grid and operating the system.

Chapter 2: *The Cost of Wind Power Plant*

THE COMPOSITION OF WIND POWER COST

Wind power is capital intensive, but the fuel is free to use. The price of wind power is more stable than the volatile prices of fossil fuel sources [16]. The marginal cost of wind energy once a station is constructed is usually less than 1-cent per kWh. Compared to traditional thermal power, wind power obviously has 2 characteristics: variability and social benefits [17].

Because of the intermittency of wind itself, the output of wind power inherits strong randomness. So wind turbines rarely provide stable flows of electricity. One way to ameliorate this issue is to provide back-up energy sources, such as a rotating reserve capacity, to ensure that a wind power system can operate reliably, maintain stability and balance demand. The increased investment cost can provide reliable wind to grid integration.

As wind is renewable, there is no need to resolve some problems caused by conventional energy generation, such as fuel availability and pollution. When calculating the benefits of wind power, these social benefits ought to be considered.

This report uses the levelized cost of electricity (LCOE) as a metric to compare different fuel sources of electricity on a consistent basis. LCOE assesses the average total cost to build and operate a power-generating asset over its lifetime, divided by the total energy output of the asset over that lifetime. The LCOE also can be regarded as the minimum cost at which electricity must be sold in order to break-even over the lifetime of the project.

The expenses and sales revenues that occur in a future time have to be accounted for the present time value of money. This can be done by employing discounted cash flow (DCF) techniques, i.e., by calculating the present value of the cash flows with a discount rate, *r* [18]. The LCOE can reflect the present value. Equation (1) suggests that the sum of the discounted revenues is equivalent to the discounted value of the sum of the costs during the economic lifetime of the system over N years:

$$\sum_{n=0}^{N} \frac{Revenues_n}{(1+r)^n} = \sum_{n=0}^{N} \frac{Cost_n}{(1+r)^n} \tag{1}$$

A Net Present Value (NPV) of the project would be:

$$\text{NPV} = \sum_{n=0}^{N} PV = 0 \tag{2}$$

The LCOE is also the average electricity price neededfor a NPV of zero so that an investor would break even and receive a return proportional to the discounted rate of the investment. The sum of the present values of the $LCOE_n$ multiplied by the energy generated annually (E_n), should be equal to the sum of the present values of the costs of the project as shown in equation (3):

$$\sum_{n=0}^{N} \frac{(LCOE_n)\times(E_n)}{(1+r)^n} = \sum_{n=0}^{N} \frac{Cost_n}{(1+r)^n} \tag{3}$$

Where r is the discount rate; n is the year; N is the lifetime of a wind farm.

Assuming a constant value for the LCOE can be defined in real terms, as equation (4):

$$LCOE = \sum_{n=0}^{N} \frac{Cost_n}{(1+r)^n} \Big/ \sum_{n=0}^{N} \frac{E_n}{(1+r)^n} \tag{4}$$

The LCOE equals to the sum of all the discounted costs incurred during the lifetime of the project divided by the units of discounted energy produced. The summation calculation starts from n=0, to include the initial cost of the project at the beginning of the first year, which should not be discounted. Of course, the initial cost could be annualized in the entire life-time of the project as shown in equation (6):

$$LCOE = \left(\sum_{n=0}^{N} \frac{CAPEX_n+OPEX_n+FIN_n+TAX_n}{(1+r)^n}\right) \Big/ \sum_{n=0}^{N} \frac{(C\times H\times(1-o_u))_n}{(1+r)^n} \tag{5}$$

Where $CAPEX_n$ is the annual value of the initial capital expenditure;

$OPEX_n$ is the annual operation expenditure;

FIN_n is the annual financial expenditure;

TAX_n is the annual tax;

C is the installed capacity;

H is the annual utilization hours;

Ou is the own usage rate;

N is the service life of the plant;

R is the discount rate.

Wind power cost, the cost of operating of a wind farm, consists of three parts: wind power project capital cost, operation and maintenance cost, and financial cost. In some nations there can be supplemental associated taxes, such as income tax, land use tax, urban construction tax, and education surcharge.

Wind power capital cost includes the infrastructure cost of wind farm, wind turbine cost, the hoisting, and commissioning cost of wind turbines, and the construction cost of grid integration. If cost reductions occur, the continuous diffusion of wind power technology and the practical application of wind power technology could become more competitive and lower its electricity cost.

Wind power are mainly decided by the capitalized cost. Taking a wind power project in United States as an example, the percentages of each factor are illustrated in figure 6 [[19]]. Wind turbine cost accounts for around 70% of the total capital cost. Infrastructure cost accounts around 9%. Operation and maintenance costs of a wind farm is relatively stable.

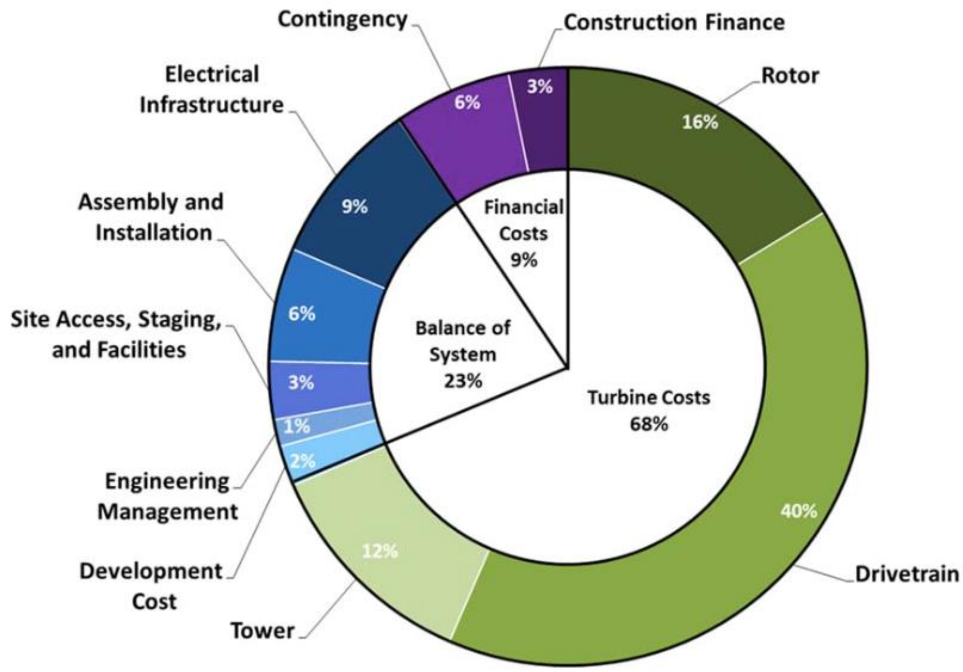


Figure 6: Capital Expenditures for the Land-based Wind Plant Reference Project

Source: Mone, C. Smith, A. Maples, B. 2013 Cost of Wind Energy Review. National Renewable Energy Laboratory. Golden, USA.

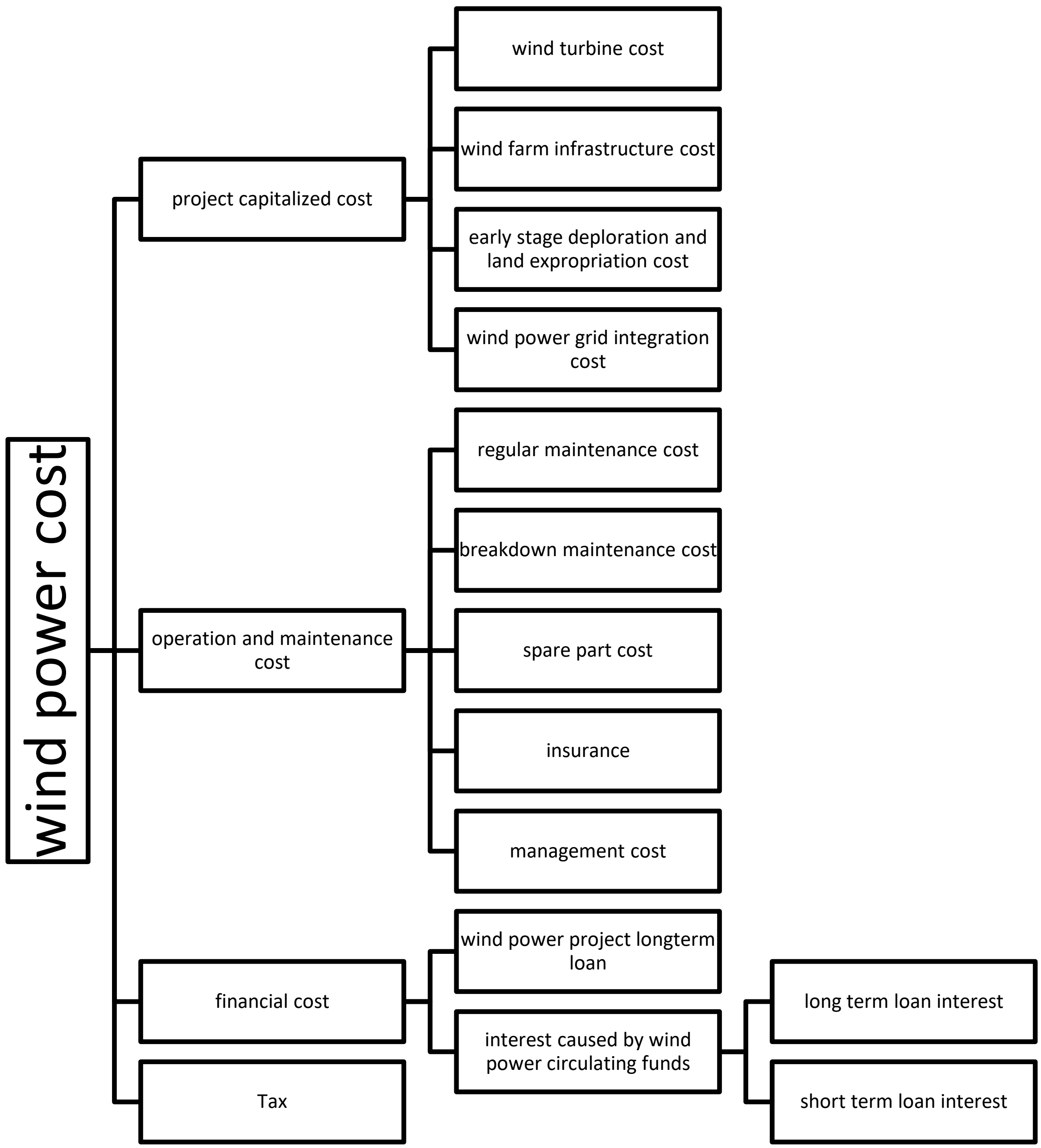


Figure 7: The Composition of Wind Power Cost [20]

Source: Sun, J. 2012. Operating Cost and Value Analysis of Wind Power. Hunan University. China.

Grid integration and social benefits of wind power can add additional cost and value to a wind power project. One cost of integration is reserve capacity cost. Reserve capacity is powered by conventional thermal units, integration cost is related to the cost of electricity generation by coal. Taking energy-saving and emission-reduction of wind power into account, the social benefit is proportional to the volume of wind power generation. Any increase in electricity caused by wind power grid integration can reduce fossil fuel consumption, reduced emissions and reduced fossil fuel consumption lead to reduced ecological effects. Some of the social benefits in wind production can be calculated by the avoided cost of repairing damages, such as health cost for coal mining workers, or prevented costs such as the cost of desulfurization. Wind power costs can be more competitive with conventional fossil fuel electricity costs as long as the social effects of wind power can be transformed into value-based costs (or benefits), or internalization of external effects [错误!未定义书签。].

WIND FARM SITE SELECTION

The profit of a wind power project will reflect by wind turbine output and the investment cost of wind turbines. Wind turbine output is decided by wind regime and the matching degree of wind energy source and wind turbine, which influence wind power cost directly. Choosing a wind farm site and suitable wind turbines are the factors to wind farm. The following flow chart illustrates the procedure of wind farm site selection:

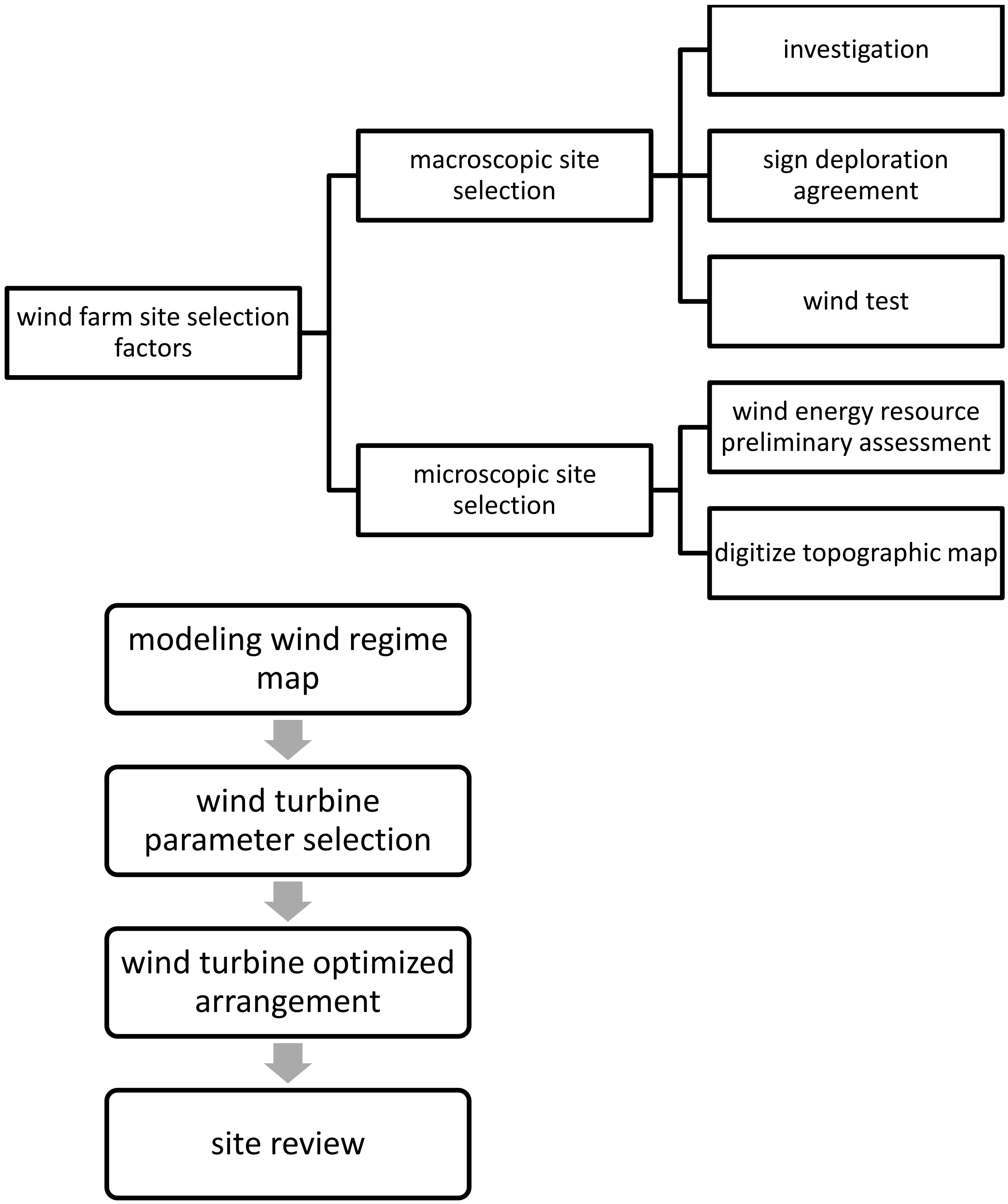


Figure 8: The Flow Chart of Wind Power Project Site Selection [21]

Source: China Wind Power Web. 2012Wind Energy Assessment of Wind Farm and Micro Siting. http://www.fenglifadian.com/news/fengdianzhishi/37572EDCF.html

WIND RESOURCE AND WIND TURBINE MATCHING MODEL

Wind power generation is different from conventional thermal power because the volume reflects the wind. Electricity generated of conventional thermal power increases as the installed capacity increases. As wind resources are not as stable as fossil fuels, wind power does not necessarily increase as the rated power output increases. For a wind farm selected the right wind turbines, can allow it make the best use of wind energy and produce maximized economic profit, it is very important to.

The capacity factor CF of a wind farm can be defined as the ratio of actual electricity generation in a period to the rated generating capacity of wind turbines. It can also be presented as the ratio of average output power P_{ave} and rated power Pr as in equation (6):

$$\mathrm{CF} = \frac{P_{ave}}{P_r} \tag{6}$$

The bigger CF is, the more economic the wind farm, and the lower the cost. P_{ave} can be expressed as the integration of the production of the power output and its frequency as indicated in equation (7).

$$P_{ave} = \int_{V_i}^{V_c} P(V)f(V)dV \tag{7}$$

Where V_i is the cut-in wind speed,

V_c is the cut-out wind speed,

P(V) is power output characteristics,

f(V) is the probability density function.

Considering the characteristics and lifetime of turbine blade, the cut-in wind speed and cut-off wind speed can be 3.5m/s and 25m/s respectively [22].

The wind turbine power output can be described as the product of the weight of the wind, its velocity and wind turbine efficiency as in equation (8):

$$P_r = \frac{1}{2}\rho C_p S {V_r}^3 \tag{8}$$

The power output characteristic can be divided into 4 parts: the cut-in wind speed, rated wind speed and cut-off wind speed of the wind turbine. When the wind velocity is below the cut-in speed or higher than cut-off speed, the electricity production is 0. When the wind velocity is between the cut-in speed and rated speed, the electricity production changes as the wind speed changes. When the wind speed is between rated speed and cut-out speed, the power output is the power at rated speed as described in equation (9).

$$\mathrm{P(V)} = \mathrm{f(x)} = \begin{cases} 0, \ 0 \le \mathrm{V} \le V_i \\ \frac{1}{2}\rho S C_p V_r^3 \eta_t \eta_g \, \eta(\mathrm{V}), \ V_i \le \mathrm{V} \le V_r \\ \frac{1}{2}\rho S C_p V_r^3 \eta_t \eta_g, \ V_r \le V \le V_c \\ 0, \qquad V \ge V_r \end{cases} \tag{9}$$

Where V_r is rated wind speed,

C_p is the efficiency of wind turbine. C_p has its limit, which is called Betz theory. In Betz theory, C_p cannot be greater than 0.593.

η_t is mechanical transmission efficiency,

η_g is the electricity transmission efficiency of generator,

ρ is the density of air,

S is the swept area of wind turbine,

$\eta(\mathrm{V})$ is wind turbine output characteristics. It can be defined as a function showing the ratio of output power to rated power when the wind speed is between start wind speed and rated wind speed.

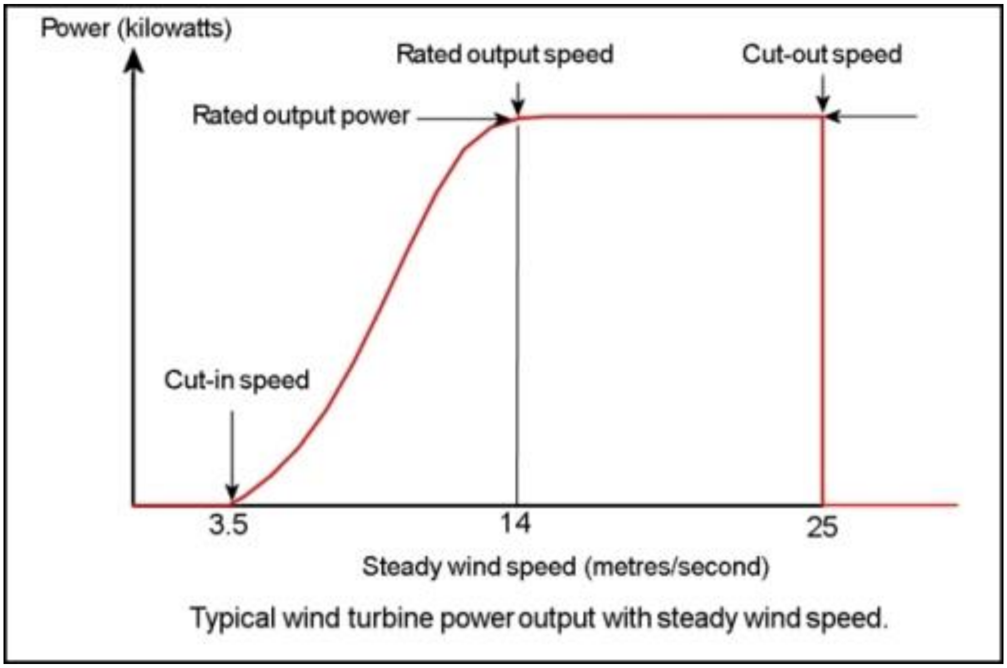


Figure 9: The static power output of 1.5MW wind turbine [22]

Source: http://www.wind-power-program.com/turbine_characteristics.htm

As illustrated in figure 9, wind turbine power output between cut-in velocity and rated velocity can be expressed as linear function, quadratic function or cubic function. This report assumes a linear expression for simplification. The difference between the wind velocity and cut-in velocity is proportional to the difference between the rated velocity and cut-in velocity as identified in equation (10).

$$\eta(V) = \frac{V-V_i}{V_r-V_i} \tag{10}$$

Weibull and Rayleigh distribution are two probability distributions often used to describe wide wind velocity. The Weibull distribution is widely used in statistical analysis; as provided by Weibull in 1951:

$$f(V) = P(V < V_i < V + dv) = P(V > 0)(\frac{k}{c})(\frac{V_i}{c})^{k-1}\exp\left[-(\frac{V_i}{c})^k\right] \tag{11}$$

Where k is shape factor,

c is scale factor.

k and c can be obtained by observation. Using maximum likelihood estimation calculating k and c, their value can be:

$$k = \left(\frac{\sum_{i=1}^{n} V_i^k \ln V_i}{\sum_{i=1}^{n} V_i^k} - \frac{\sum_{i=1}^{n} \ln V_i}{n}\right)^{-1} \tag{12}$$

$$c = \left(\frac{1}{n}\sum_{i=1}^{n} V_i^k\right)^{1/k} \tag{13}$$

When evaluating wind resource, the wind velocity V at the height of the wind turbine blades is usually not the tested velocity. Equation (14) allows an analyst to derive the velocity at the height of blades. The ratio of the velocity at the height of blades to the velocity at the tested height equals to the exponential of the ratio of their heights as described in equation (14).

$$V = V_t\left(\frac{H}{H_t}\right)^{\propto} \tag{14}$$

Where $\propto$ is the height factor, which is decided by topography. The coefficient $\propto$ is usually taken as 1/7.

V_t is the velocity at tested height and H_t is the tested height. V is the velocity at blades and H is the height of blades.

As a result, CF can be expressed as in equation (15):

$$CF = \frac{1}{{V_r}^3}\int_{V_i}^{V_r} V^3 f(V)dV + \int_{V_r}^{V_c} f(V)d(V) = \frac{e^{-(\frac{V_i}{c})^k} - e^{-(\frac{V_r}{c})^k}}{(\frac{V_r}{c})^k - (\frac{V_i}{c})^k} - e^{-(\frac{V_c}{c})^k} \tag{15}$$

WIND POWER COST MATHEMATICAL MODEL

Capital Expenditure

The investment cost of a wind power project C_n typically will reflect the costs of wind turbine cost C_t, wind farm construction cost C_i, early stage development and land cost C_l and wind power grid integration cost C_g. as described in equation (16).

$$C_n = C_t + C_i + C_l + C_g \tag{16}$$

Equation (17) defines that the electricity generated by wind turbines is the product of wind turbine rated capacity and the number of effective hour of capturing wind energy:

$$Q_w = 8760 \times \mathrm{CF} \times P_r \tag{17}$$

The number of effective hour is the product of the number of the hour in a year by capacity factor as shown in equation (18):

$$\mathrm{H} = 8760 \times \mathrm{CF} \tag{18}$$

Assuming the lifetime of a wind farm is N years, the electricity generated during lifetime is the product of the year and its annual electricity production as indicated in equation (19):

$$\mathrm{Q} = \mathrm{N} \times Q_w \tag{19}$$

The large fraction of the investment is the wind turbine. Assuming the ratio of wind turbine cost to total investment is K, then:

$$\mathrm{K} = \frac{C_t}{C_n} \tag{20}$$

During project planning, wind turbine cost can be determined, so the capital expenditure can be determined as well as indicated in equation (21).

$$CAPEX_n = C_n = \frac{C_t}{K} \tag{21}$$

For a wind power project of which the investment is settled, the factors that influence unit investment cost are discount rate r, wind power project depreciation time n, capacity factor CF, wind farm lifetime N and rated capacity P_r. Depreciation time, wind farm lifetime and rated power is settled during wind farm planning. However, discount rate is decided by financial policy. One way to lower unit investment cost, we can change capacity factor CF to achieve a lower cost.

Operation and Maintenance Expenditure

Wind turbines, like any other industrial equipment, need cost to operate and maintain. In the early stage, O&M cost accounts for 10% to 15%., when a wind facility is approaching wind turbine lifetime after abrasion and aging for a long time, the O&M cost can account for 20% to 35% of all the cost [23].

Operation and maintenance cost mainly consists of regular repair charges, fault maintenance cost, spare parts cost, insurance cost and management cost. It is easy to calculate insurance cost and management cost within wind turbines' lifetime. Fault maintenance cost and spare parts cost is hard to predict. Wind turbine system reliability is a critical factor in the success of a wind energy project. Poor reliability directly affects both the project's revenue stream through increased operation and maintenance (O&M) costs and reduced availability to generate power due to turbine downtime. Usually, insurance cost and regular maintenance cost and management cost are relatively stable.

According to the conventions of the electric power industry, the insurance rate is 0.25% of the total investment [24]. According to the design standard of wind farms, the maintenance rate is between 1.5% and 2% [24]. For standard staffing, a typical wind farm needs one frontline worker for every 10MW of capacity and the ratio between frontline and administrative staff is 10:2 [24]. This standard leads to a staff of 12 workers for a 100MW wind farm. The average annual salary is set as 80000yuan/yr. Other fixed cost is set as 0.02 yuan/KWh [24].

Financial cost of wind power

Financial loan expenses include long-term loan interest and short-term loan interest. Financial costs in wind power project are the interest of long-term loans incurred during the project construction and the interest of working capital loans during the project's operating life. During the construction period of the project, the interest generated by the loan refers to the interest of the raised funds that accrue during the construction period. They will be included in the original value of the fixed assets after it is put into operation.

The charge includes capitalized interest, including bank loans, other debts interest and other financial costs.

Construction interest is based on the construction investment year and investment volume in each year, according to project schedule. One simplified approach is to assume the loan is spent in the middle of the year. This allows loan interest to be calculated on the basis of half-year interest in year 0, and on an annual basis of the remaining years. Under normal circumstances, interest is calculated using compound interest. The sum of principal and the cumulative total interest of the previous period as indicated in equation (22).

$$l_n = (L_n + b_n/2) \times R_i \tag{22}$$

Where l_n is the interest of each year;

L_n is the accumulative amount of principal and interest of the loan at the beginning of the year;

b_n is the loan of this year;

R_i is the effective annual interest rate as indicated in equation (23).

$$R_i = (1 + \frac{R}{m})^m - 1 \tag{23}$$

where R is annual interest rate;

m is the time calculating interest each year.

The loan interest rate increases, interest increases, and so will the cost of wind power will.

Working capital refers to the difference of current assets and current liabilities. Working capital can be used to purchase raw materials, pay wages and other expenses after a project is in operation. As wind farm uses wind which is free, the working capital of wind power project is relatively small. To simplify calculation, this report uses index expansion method described in equation (24) to assess working capital of wind farm. The ratio of the fixed assets of the planned project to its scale, equals to the production of a price conversion factor and the ratio of the fixed assets of the comparable project to its scale

$$m_2 = n_2(m_1/n_1)W \tag{24}$$

Where m2 is the fixed assets of the panned project per unit;

n2 is the scale of the planned project;

m1 is the fixed assets of the comparable project per unit;

n1 is the scale of the comparable project;

W is the price conversion factor.

Thus, working capital is the production of the fixed assets of the panned project and the total capacity described in equation (25).

$$A_w = m_2 \times C \tag{25}$$

Where A_w is working capital.

Initial working capital is the need at the beginning of project operation. To make sure enough working capital after trial, it usually accounts for 30% of the total working capital, the rest comes from bank loan. In China, bank will only loan 70% of the working capital. Working capital is actually long-term loan. Its annual interest can be calculated using the production of the loan balance and the interest rate in equation (26):

$$s_n = A_{bn} \times R_w \tag{26}$$

Where s_n is annual working capital interest;

A_{bn} is working capital balance at the beginning of each year;

R_w is working capital interest rate.

Assuming the repayment is the same each year, the working balance is the difference between total borrowed working capital and the paid loan. The paid loan is derived using equal principle and interest method. Working capital balance can be calculated in equation (27).

$$A_{bn} = 70\%A_w - (n-1)70\%A_wR_w(1+R_w)^N/((1+R_w)^N-1)(27)$$

To complete the total financial cost during the planning period in equation (28), the financial budget will include the sum of working capital, construction loan interest and working capital loan interest.

$$FIN_n = A_w + \sum_{n=1}^{N} l_n + \sum_{n=1}^{N} s_n \tag{28}$$

Tax

According to the tax code in China, there are various tax policies for wind power project. During the operation, five types of tax need to be paid. They are value-added tax, income tax, sales tax and additional tax, property tax and land tax.

Value added tax is 17% with 50% exemption calculated in equation (29). The 50% exempted tax will be returned after the value-added tax is paid. The tax base is annual income deduced by intermediate cost and fixed assets investment.

$$T_v = (R_n - C_n) \times 50\% \times 17\%/(1+17\%) \tag{29}$$

Where R_n is the revenue of the nth year.

For the income tax calculated in equation (30), there is full exemption for the first three operation years, and half exemption for the second three half years. Otherwise, the tax is 15%.

$$T_I = \begin{cases} 0, \ 1 \leq \mathrm{n} \leq 3 \\ 50\% \times 15\% \times R_n, \ 4 \leq \mathrm{n} \leq 6 \\ 15\% \times R_n, \ 7 \leq \mathrm{n} \leq \mathrm{N} \end{cases} \tag{30}$$

Sales tax and additional tax calculated in equation (31) are based on value-added tax. For a wind power project, there are urban construction tax and education surcharge. The urban construction tax is 5% and the education surcharge for central and local government are 3% and 1% respectively. There are a total of 9%.

$$T_s = T_v \div 50\% \times 9\% \tag{31}$$

Property tax is 1.2% with 30% exemption calculated in equation (32). The tax base is land and building assets.

$$T_p = 1.2\% \times (1 - 30\%) \times V_p \tag{32}$$

Where V_p is the value of land and building assets.

Land use tax is 2 yuan/m2 for non-cultivated land or 12 yuan/m2 for cultivated land calculated in equation (33).

$$T_l = \begin{cases} 2 \times S_l, & \text{non} - \text{cultivated land} \\ 12 \times S_l, & \text{cultivated land} \end{cases} \tag{33}$$

where S_l is the area of land use.

Wind farm can choose non-cultivated land to save money.

The Kyoto protocol, which came into effect in 2005, introduced the Clean Development Mechanism (CDM), is a mechanism for developed countries to collaborate with developing countries to meet their GHG emission reduction obligations through project cooperation to promote the achievement of the objectives of the United Nations Framework Convention on Climate Change. CDM can help developing countries to achieve sustainable development and assist developed countries to meet their commitment to quantify restrictions and reduce greenhouse gas emissions. The CDM income of a wind power enterprise is the income of CERs (Certificated Emissions Reductions), which reflects certified income from emission reductions. A wind power enterprises does not need to pay business tax for CDM income. To relieve the pressure from wind and solar abandoning, the Chinese government issued a renewable energy green credit and voluntary trading policy in 2017. 1000 kWh equals to 1 green credit. Trading green credit is exempt from tax. The green credit price upper limits of each province are listed in table 1.

Province	Green Credit Price upper limit ($/MWh)
Heilongjiang	18
Gansu	23
Inner Mongolia	16
Zhejiang	23
Hunan	18
Xinjiang	18

Table 1: Green Credit Price Upper Limit of Each Province

Source: Bloomberg New Energy Finance

CONCLUSION

The factors influencing wind power cost are the wind turbine cost, construction cost, design lifetime, wind resources, operation reliability, operation cost, maintenance cost and interest. As the scale of wind turbine increases, equipment cost reductions lowered cost. These strategies can reduce the cost of changing wind power.

Wind turbine cost accounts for most in investment cost. Turbines made in China has a lower price than other countries listed in Figure 10 [[25]][[26]]. Turbines also exhibit an improved installed capacity and technological level, adopting high quality domestic wind turbines can reduce investment and depreciation cost effectively, so that wind power price can compete with conventional thermal power.

Figure 10: Wind Turbine Cost in Selected Countries, 2008 and 2010

Source:

IEA Wind. 2009. IEA Wind: IEA Wind: 2008 Annual Report, IEA Wind Energy Systems.

IEA Wind. 2011. IEA Wind: IEA Wind: 2010 Annual Report, IEA Wind Energy Systems.

The best site for a wind turbine is a site where wind resource is abundant. Wind resource can influence wind farm power output directly. For example, wind turbines with same installed capacity can generate more electricity in an area with abundant wind, which lead to higher economic benefit.

Wind operation cost can save money by improving equipment structure, increasing reliability and reducing operation and maintenance cost. Countries like Germany, Denmark and United States conduct research on the relation between wind turbine design and wind power cost. Wind turbines optimized design that reduce weight and cost can save funds.

Designs of turbine blades, drive system, as well as cabin and tower design can have most impact on wind turbine. Wind turbine designs can also should improve reliability and reduce wind power cost. Operation and maintenance cost accounts for 15% to 25% in total cost. Many factors would affect steady operation and increase maintenance cost, for example, dust, high temperature and corrosion. We need to make practical contingency plan to eliminate operational hidden danger and enhance risk control, to extend equipment lifetime and reduce O&M cost.

Chapter 3: *Integration Cost and Environmental Value*

Compared to a conventional coal fire plant, a wind farm possesses variability and social benefits.

Intermittent power output of wind turbines shows strong stochastic and fluctuation behavior. Fluctuation undermines voltage stability and grid frequency. To keep a stable operation of the grid after wind power integration, reserve capacity can compensate for fluctuations caused by intermittency of wind energy source.

Wind energy is a clean energy, compared to coal, oil and natural gas as sources for electricity. The wind power as a fuel is free to use. As a result, wind power can generate "environmental value" which means the benefit brought by less production of pollution and carbon dioxide.

In China, most of the large-scale wind farms are far away from population center. Large-scale wind farms have gigawatt-capacity and may transfer electricity for hundreds to thousands of kilometers.

We can see that many wind farms locate in northwestern part and northeastern part of China In figure 10 [[27]], while the electric loads locate mainly in east part of China. This causes the uneven distribution of energy. Unlike Europe where wind power is scattered geographically, wind farms in China are built on a much larger scale.

Figure 11: Map of Ten Million Kilowatt Wind Farm Distribution in China

Source: National Energy Administration. 2007. New Energy Industry Revitalization Plan. Beijing, China

INTEGRATION PROBLEMS

There are 3 main problems integrating wind power into a grid, voltage flicker, harmonic pollution and voltage stability.

Most wind turbine generators use a soft-integration approach, but still can cause a large inrush current at start-up. When the wind speed exceeds the cut-out wind speed, the turbine will automatically withdraw from the rated output operation. If all the wind turbines in wind farm act like this simultaneously, there will be a significant impact on the grid network. Other than that, the change in wind speed and tower effect of turbines will cause output fluctuation. This fluctuation is within the frequency range which can cause voltage flicker. Therefore, wind turbines can cause flicker problems even during normal operation [28].

Wind power brings a harmonic wave to the system in two ways. First, the electronic devices equipped on wind turbine may bring harmonic problems. For a fixed-speed wind turbine connected directly to the grid, it needs to be connected to the grid through electronic devices in the soft-start phase, resulting in a certain degree of harmonics. But this process is short and tmay be irregular and without many occurrences, so the harmonic problem caused by fixed speed wind turbines can be negligible. Harmonic issue can be different for variable–speed wind turbines. The generator of variable-speed wind turbine is connected to the system through rectifier and inverter device. If the frequency of electronic devices is within the frequency range that could cause a harmonic disturbance which can result in very serious harmonic problems. The parallel compensating capacitor of a wind turbine may resonate with the line reactance. However, compared with the problem of voltage flicker, the harmonic problem brought by integration is not so serious [29].

Wind power output changes as wind velocity changes. Because wind farms are mostly built at the end of the grid, short circuit capacity is relatively small so that the stability and quality of grid voltage will be influenced. Induction generators used in wind turbines need reactive power to compensate. So a wind turbine\ integrated into the grid is a reactive load for the grid [30].

WIND CURTAILMENT

Due to the lack of infrastructure, many wind turbines are abandoned after construction. Although China officially advocates wind power development, the practical electricity generation has not reach Chinese government's expectation. Many countries have experienced large-scale wind curtailment problems. Figure 11 illustrates that although the wind curtailment rate of Texas has reached up to 17% in 2009 [31]. Technological problems and political obstructions can prevent the process of successful wind power integration are. In China the wind power price is decided by the central government, so that it cannot change with demand or thermal power price. Chinese gird dispatch departments set a high minimum electricity generation for coal fire plants through administration, so that the wind power generation is very limited.

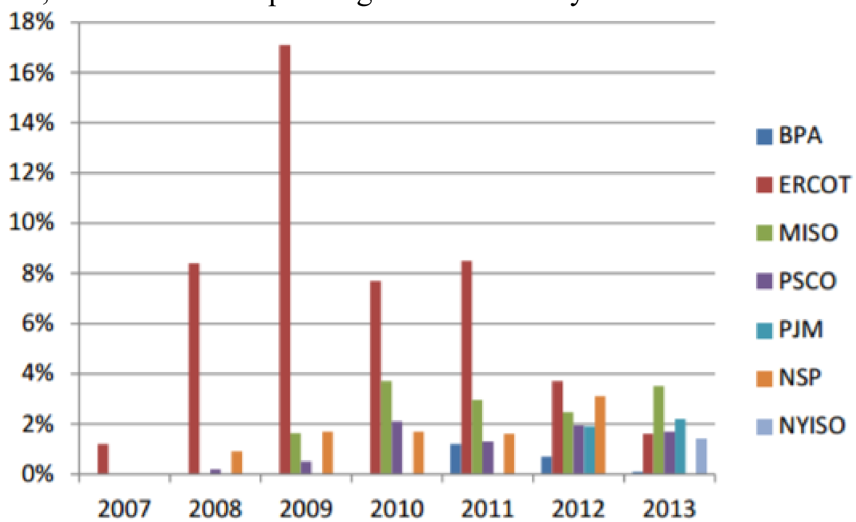


Figure 12: Curtailment as Fraction of Wind Generation

Source: Bird, L. Cochran, J. Wang, X. 2014. Wind and Solar Energy Curtailment: Experience and Practices in the United States. National Renewable Energy Laboratory.

From a political point of view, two proposals from published by State Council may have consequences on wind power cost. One is to reduce the amount of planned wind energy quotas. The other one is to allow market-determined generation tariffs gradually. Regulatory changes to bring grid companies more in line with international best practices are also important to eliminate conflicts of interest in dispatching power plants. If China reduces the minimum output level of coal plants and makes more frequent and flexible scheduling decisions, wind alone could reach 14% of primary energy in 2030, almost three quarters of the way toward its 2030 target which is to make renewable energy account for 20% of total energy consumption [32]. More price flexibility would allow wind farms to make independent pricing decisions. China's current thermal-based power generation structure and large-scale power transmission makes it hard to accept intermittent power. Increasing amounts of more flexible power supplies, such as gas power plants and increasing multi-energy system integration, would help.

SOLUTIONS FOR INTEGRATION PROBLEMS

Technologies

Wind energy penetration refers to the percentage of demand covered by wind energy in a certain region, normally on an annual basis as indicated in equation (34).

$$\text{Wind energy penetration} = \frac{total\ amount\ of\ wind\ energy\ produced}{gross\ annual\ electricity\ demand} \quad (34)$$

From the reliability perspective, at a relatively low penetration level, the net-load fluctuations are comparable to existing load fluctuations [33]. During this phase, conventional generators, such as thermal power plants and hydro power plants, have sufficient load tracking capability without requiring additional operating reserve. By September 2016, wind penetration rate in China had reached 4.36%, much smaller than the 42.1% penetration in Denmark in 2015. Figure 13 illustrates the wind power penetration rate has increased to 3.33% in 2015, and it is likely to increase steadily.

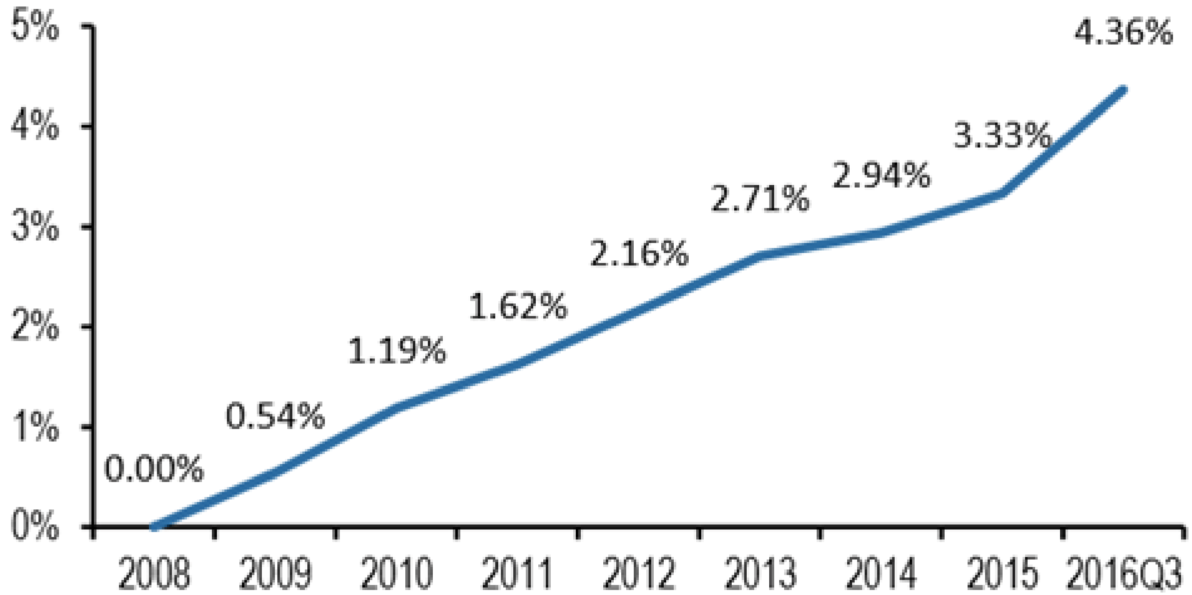


Figure 13: Wind Penetration Rate from 2008 to 2016 in China

Source: National Energy Administration

As the wind penetration level increases, the response time of conventional generators is required to be short enough to compensate for sudden changes of wind power output.

Storage technologies

To deal with wind integration problems, option to store excess wind power might be a good solution. From a technological point of view, an Energy Storage System (ESS) has the ability of flexible charging and discharging. Excess electricity generated by wind can be stored in storage systems and can be used when the wind blows down. The electrical energy can be stored in different energy forms: mechanical electro-chemical, chemical, electromagnetic, thermal, etc. Figure 14 illustrates that the classification of energy storage technologies according to the stored energy form [34]. Four widely used energy storage technologies are discussed below.

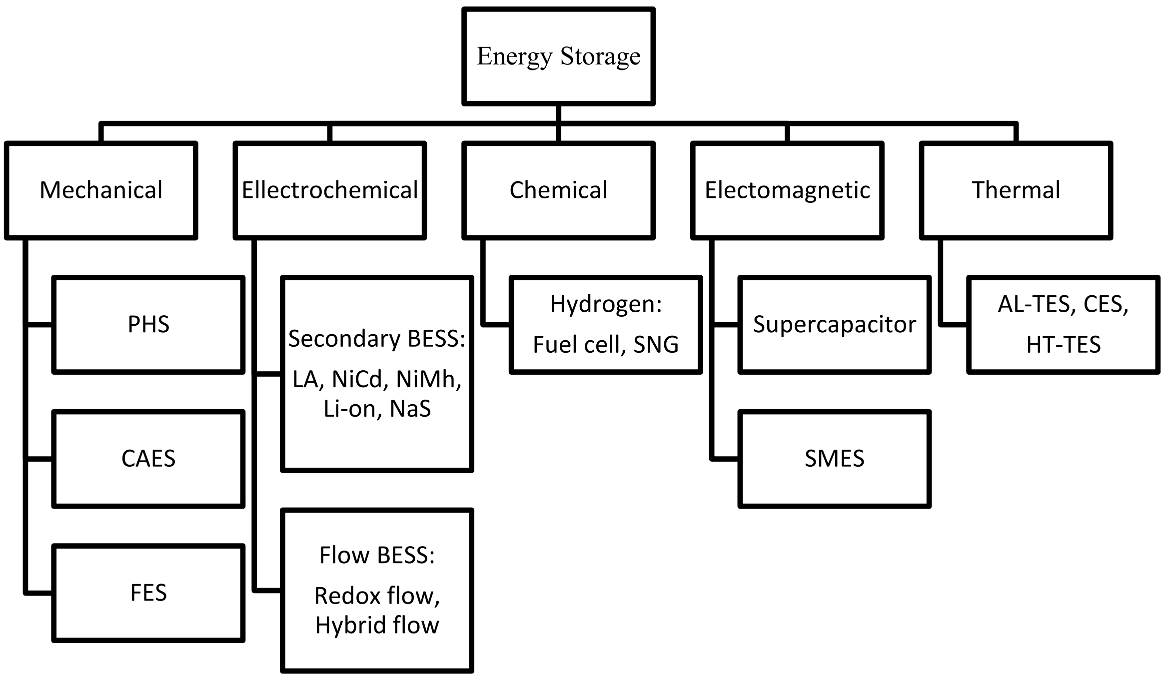


Figure 14: Energy Storage Classification

Source: International Electrotechnical Commission. 2012. Grid Integration of Large-capacity Renewable Energy Sources and use of Large-capacity Electrical Energy Storage, Tech Report.

Pumped Hydro Storage (PHS) is the most widely deployed grid-scale energy technology. It is a type of hydroelectric energy storage used by electric power systems for load balancing. The method stores energy in the form of gravitational potential energy of water, pumped from a lower elevation reservoir to a higher elevation. Low-cost surplus off-peak electric power is typically used to run the pumps. During periods of high electrical demand, the stored water is released through turbines to produce electric power.

Compressed Air Energy Storage (CAES) is a technology that uses electrical compressors to compress air and store it within an underground structure or above-ground system of vessels or pipes. When needed, the compressed air is released. It can be mixed with natural gas, burned and expanded in a modified gas turbine.

Flywheel Energy Storage (FES) works by accelerating a rotor (flywheel) to a very high speed and maintaining the energy in the system as rotational energy. When energy is extracted from the system, the flywheel's rotational speed is reduced to drive the machine as a generator.

Battery Energy Storage System (BESS) stores electricity in the form of chemical energy. It includes Lead Acid battery, Nickel Cadmium battery, Nickel Metal Hybrid battery, Lithium Ion battery and Sodium Sulphur battery.

Table 2 [[35]] illustrates the compensate costs of energy storage methods. Compressed air energy storage is relatively cheap among others at a capital cost from 2 to 50 dollars per kilowatt hour. Compared to battery energy storage systems, such as LA, NiCd, Li-om and NaS, whose capital costs range from 200 to 2500 dollars per kilowatt hour, CAES has lower cost per stored kWh. Pumped hydro storage is also relatively inexpensive with a capital price ranging from 5 to 100 dollars per kilowatt hour. However, it is limited by geological factors. In China, many large-scale wind farms located in places where water resources in short supply.

System	Capital Cost ($/kWh)
Pumped Hydro Storage	5-100
Compressed Air Energy Storage	2-50
Flywheel Energy Storage	1000-5000
Battery Energy Storage System	200-2500

Table 2: Capital Cost of ESS

Source: Zhao, H. Wu, Q. Hu, S. et al. 2015. Review of Energy Storage System for Wind Power Integration Support. Applied Energy 137 (2015) 545-553.

Most of the CAES projects that have been built or is planned are locate in the United States and Europe. Although there is no large scale CAES projects built in China, the second term of Zhangbei Wind and Solar Energy Storage Project might be the biggest CAES project in the world when it is completed. National Grid is working on high-efficiency evaporator and condenser, which will reduce related costs greatly if this technology is successfully developed. Unlike conventional CAES, this new technology will liquefy air and recoup waste heat in compressing process and waste cold energy in expending process at the same time. The system efficiency will be improved greatly. The system energy density could reach 100Wh/L, which is 20 times denser than conventional CAES energy density. The efficiency of transferring electricity could reach 50% to 60% [36].

Reserve capacity

Energy storage technologies are not mature and too expensive to compensate for changes in wind power production in 2017. So a wind farm still need to use reserve capacity to balance when the wind fails to blow. Reserve capacity or reserve margin of electricity power system is the capacity that can guarantee the demand of electricity market when electricity system is under maintenance, due to outages, or to maintain frequency regulation. It is a measure of available capacity over and above the capacity needed to meet normal peak demand levels.

Reserve capacity includes maintenance reserve capacity, contingency reserve capacity and load reserve capacity. Maintenance reserve capacity is designed to satisfy the capacity demand during regular planned maintenance. Contingency reserve capacity is used to take the place of units that is out of power to ensure system stability. Load reserve capacity is used to satisfy the demand caused by the sudden change in electricity system load. The type of reserve capacity can also be divided by the status of reserve capacity.

Two types of reserves are are spinning reserve and non-spinning reserve. Spinning reserve is the extra generating capacity that is available by increasing the power output of generators that are already connected to the power system. It is the biggest difference between the maximum power available and the maximum load. Non-spinning reserve is the extra generating capacity that is not currently connected to the system but can be brought online after a short delay.

Generators that intend to provide either spinning or non-spinning reserve should be able to reach their promised capacity within roughly ten or thirty minutes, respectively. Most power system guidelines require a significant fraction of their operating reserve to come from spinning reserve [37]. This is because the spinning reserve is slightly more reliable (it doesn't suffer from start-up issues) and can respond immediately whereas with non-spinning reserve generators there is a delay as the generator starts-up offline. Spinning reserve can be divided as positive reserve and negative reserve. When the practical power output is greater than prediction, reducing the output of thermal units can optimize wind resource usage and help keep electricity system stable. The reduced output in thermal units is negative spinning reserve capacity.

In the environment of electricity market, reserve capacity can be bought by grid companies from power stations as an auxiliary service. Grid companies may need to pay capacity cost and electricity cost for this service [38].

Reserve capacity is equal to installed capacity minus peak load

The integration cost should be the sum of reserve capacity cost, start-up cost and electricity generation cost [39]. The reserve capacity cost can be calculated using equation (35):

$$\min C_g = \sum_{t=1}^{X}\sum_{i=1}^{Y}\left[\left(u_{i,t}O_{i,t}\left(P_{i,t}\right) + u_{i,t}\left(1-u_{i,t}\right)C_i^s + (\rho_i^{up}R_{i,t}^{up} + \rho_i^{dn}R_{i,t}^{dn})u_{i,t}\right]\quad(35)$$

Where the first term $u_{i,t}O_{i,t}\left(P_{i,t}\right)$ is the generation cost of thermal unit i during period t;

The second term $u_{i,t}\left(1-u_{i,t}\right)C_s$ is the start-up cost of thermal period i;

The third term $(\rho_i^{up}R_{i,t}^{up} + \rho_i^{dn}R_{i,t}^{dn})u_{i,t}$ is reserve capacity cost of thermal unit i during period t.

X is the number of periods in a dispatch cycle;

Y is the number of total thermal units;

$P_{i,t}$ is the power output of thermal unit i during period t;

$O_{i,t}\left(P_{i,t}\right)$ is the cost function of thermal unit i;

$u_{i,t}$ is the status of operation, it could be 0 or 1; 1 represents on and 0 represents off;

C_i^s is the cost of start-up of thermal unit i;

ρ_i^{up} and ρ_i^{dn} are the cost of positive reserve and negative reserve;

$R_{i,t}^{up}$ and $R_{i,t}^{dn}$ are the amount of positive and negative reserve.

$O_{i,t}\left(P_{i,t}\right)$ can be represented as equation (36):

$$O_{i,t}\left(P_{i,t}\right) = a_iP_{i,t}^2 + b_iP_{i,t} + c_i \quad (36)$$

where a_i, b_i and c_i are fixed factors of thermal units.

These are subjected to constraints as discussed below.

(1) System Power Balance

The system power balance means The sum of the power output of thermal units and the power output of wind farms is the total power load as described in equation (37).

$$\sum_i^Y P_{i,t} + \sum_k^Z P_{k,t} = P_{L,t} \tag{37}$$

Where $P_{k,t}$ is the power output of wind farm k during period t;

Z is the number of wind farms;

$P_{L,t}$ is the power load during period t.

(2) Output

The power output of thermal units should be in the range of their minimum and maximum output as indicated in equation (38).

$$u_{i,t}P_i^{min} \leq P_{i,t} \leq u_{i,t}P_i^{max} \tag{38}$$

Where P_i^{min} and P_i^{max} are the minimum and maximum output limit of thermal unit i;

(3) Ramp Rate

The ramp rate constraint means the power changing rate between 2 periods has to be in the range of downward ramp rate and upward ramp rate as indicated in equation (39). It means that it cannot increase too fast or too low.

$$-P_{i,dn} \leq P_{i,t} - P_{i,t-1} \leq P_{i,up} \tag{39}$$

Where $P_{i,dn}$ and $P_{i,up}$ are the downward ramp rate and upward ramp rate;

(4) Reserve capacity demand

The reserve capacity demand constraint means that the sum of positive and negative reserve capacities have to be greater than the minimum demand of positive and negative reserve capacity respectively as shown in equation (40) and (41).

$$\sum_i^X u_{i,t} R_{i,t}^{up} \geq R_{LD,t}^{up} \tag{40}$$

$$\sum_i^X u_{i,t} R_{i,t}^{dn} \geq R_{LD,t}^{dn} \tag{41}$$

Where $R_{LD,t}^{up}$ and $R_{LD,t}^{dn}$ are the minimum reserve capacity of positive and negative spinning reserve capacity

(5) Reserve capacity limit

Equation (42) and (43) illustrates reserve capacity limit constraints. The allocated reserve capacity of unit *i* during period *t* cannot exceed the maximum capacity it can provide in this period. The maximum capacity of positive capacity is the smaller one between the difference between maximum power output and the power output in period t, and the upward ramp rate. The maximum capacity of negative capacity is the smaller one between the difference between the power output in period t and the minimum power output, and the downward ramp rate.

$$0 \leq R_{i,t}^{up} \leq \min(P_i^{max} - P_{i,t}, P_{i,up}) \tag{42}$$

$$0 \leq R_{i,t}^{dn} \leq \min(P_{i,t} - P_i^{min}, P_{i,dn}) \tag{43}$$

(6) Frequency of operation and down time

The frequency of operation and down time constraint in equation (44) and (45) indicates that the thermal units need minimum operation time and minimum rest time. If an operating unit turns off, the time it is on has to be greater than the minimum operation time. If a down unit turns on, the time it is off has to be greater than the minimum down time.

$$\left(u_{i,t-1} - u_{i,t}\right)\left(T_{i,t-1}^{on} - T_i^{on}\right) \geq 0 \tag{44}$$

$$\left(u_{i,t} - u_{i,t-1}\right)\left(T_{i,t-1}^{off} - T_i^{off}\right) \geq 0 \tag{45}$$

$T_{i,t-1}^{on}$ and $T_{i,t-1}^{off}$ are the time thermal unit i has spent in period t.

T_i^{on} and T_i^{off} are the minimum continuous operation time and the minimum continuous down time of thermal unit i during time t.

(7) Output of a Wind Farm

The output of a wind farm constraint means that, wind farms need active power adjustment ability as required in *Technical Principles of Wind Farm Electricity System Integration* by National Grid,. It has to be smaller than the predicted active power of the wind farm as shown in equation (46).

$$0 \leq P_{k,t} \leq w_{k,t} \tag{46}$$

$w_{k,t}$ is the active power of wind farm k predicted at period t.

(8) Power limit of the line

The power limit of the line means that the total load has to be smaller than the power limit of the line as indicated in equation (47).

$$P_{L,t} \leq P_{l,max} \tag{47}$$

$P_{l,max}$ is the maximum of the line.

ENVIRONMENTAL VALUE

China's current production and use of coal has led to damages in mining area. Large area of land and vegetation have been damaged. Ground water is polluted by coal mining waste water. Coal mining can also lead to land collapse, solid waste pollution, and air pollutions.

China's current environmental economic policy has not yet been implemented enough to collect more charges from coal companies for their environmental damages. China has implemented some tax policies that are conducive to environmental purposes, such as sewage charges, resource taxes, sustainable development funds, etc.. However, from the aspect of actual environmental damage caused by coal, these polices are far from enough to address the external environmental costs generated by coal production and use.

Environmental value is a monetized environmental benefit and interpreted as the value derived from pollutant emission reduction [40]. The environmental value of wind power can be regarded as an environmental cost of coal or in this report, a cost saved by wind replacing coal. As a result, the environmental value of a wind farm can be expressed using equation (48):

$$C_{env} = C_{\mathrm{pro}} + C_{tran} + C_{use} \tag{48}$$

where C_{env} is the total environmental cost, C_{pro} is the environmental cost incurred in coal production, C_{tran} is the environmental cost incurred in coal transportation, C_{use} is the environmental value incurred in coal use.

With the help from Energy Foundation, Environment Protection Department of Environmental Planning Institute conducted a research on the external environmental cost of coal in 2010. They evaluated different types of pollutions in coal mining, coal transportation and coal use. The heaviest loss is the health damage caused by air pollution, estimated at 305 billion yuan, accounting for 55% of the total external environmental cost. The total external environmental cost was 555.5 billion yuan. In the stage of production, the cost was 218.6 billion yuan, which was 39.4% of the total cost. Transportation costs 71.4 billion yuan, which was 12.9% of the total cost. In the stage of use, the cost was 265.5 billion yuan, which was 47.8% of the total cost [41].

Pollution quantify

Conventional coal power plants produce large amount of sulfur dioxide, Nitrogen oxides, carbon dioxide, carbon monoxide, dust, and Total Suspended Particulates (TPS), causing serious pollution to the environment. The following equations and parameters are from Sewage Charge Standard promoted by the State Council [42].

Sulfur dioxide is defined as an important pollutant. Sulfur dioxide emitted by coal accounts for a large part of national industrial sulfur dioxide emission in China. What affects most in SO_2 emission is the sulfur content in coal, followed by flue gas conversion rate. SO_2 emission rate can be calculated using equation (49):

$$G_{SO2} = B \times S_y \times K_{SO2} \times \lambda_{SO2} \times (1 - \eta) \tag{49}$$

where G_{SO2} is the emission of SO_2, kg;

B is the coal used, metric ton;

S_y is the mass fraction of sulfur in coal;

K_{SO2} is the conversion rate of sulfur in coal to SO_2;

λ_{SO2} is the molar mass ratio of sulfur dioxide to sulfur, which is round 2;

η is desulfurization efficiency.

To estimate sulfur dioxide emission rate per ton of coal, China stipulates that the sulfur content of standard coal S_y is 1%. Flue gas desulfurization is the most widely used and the most efficient method of desulfurization. Using the wet process, the desulfurization rate can reach to 90% to 98% [[43]]. This report assumes $\eta = 0.9$. As a result, the SO_2 emission rate of a regular coal fire plant would be 18kg/t. If this power plant installed desulfurization facilities, the SO_2 emission rate would be 1.8kg/t.

NO_x is the second largest pollutant, which mainly includes NO and NO_2. NO accounts for 95% of NO_x. There are three main ways to form it: nitrides in coal being decomposed and oxidized during combustion; nitrogen in the air being oxidized at high temperature; CH atom particles, oxygen and nitrogen forming NO_x. When generating electricity in thermal power plants, nitrogen in coal is the main source of NO_x. It usually accounts for more than 75% of total NO_x emission. As assumed, nitrogen conversion rate would be 25% [[44]]. NO_x can be calculated by equation (50):

$$G_{NOX} = 1.63 \times B \times (N_y \times \eta_N + 0.000938) \tag{50}$$

where G_{NOX} is NO_x emission, kg;

N_y is the mass fraction of nitrogen in coal;

η_N is the conversion rate of nitrogen in coal to NO_x;

The mass fraction of nitrogen in coal N_y is approximately 0.85%; the conversion rate of nitrogen in coal to NO_x η_N is approximately 70%. So in normal situation, NO_X emission rate would be 18.64kg/t.

For greenhouse gas carbon dioxide, its emission can be calculated using equation (50):

$$G_{CO2} = B \times Q \times E \times K_{CO2} \times \lambda_{CO2} \tag{51}$$

Where G_{CO2} is the emission of CO_2, kg;

Q is the unit heating value of coal, MJ/kg;

E is carbon emission, t/Tj

K_{CO2} is carbon oxidation rate;

λ_{CO2} is the molar mass ratio of carbon dioxide to carbon, which is about 3.667;

The average unit heating value of coal Q is 21.2 MJ/kg; the potential carbon emission per unit heating value E is 24.74 t/Tj. The carbon oxidation rate K_{CO2} is 0.9 [45]. As a result, the emission rate of carbon dioxide is 1731kg/t. For dust in coal, it can be calculated by equation (52):

$$G_{dust} = B \times A \times d_{fh}(1 - \eta_{fh})/(1 - C_{fh}) \tag{52}$$

where G_{dust} is dust emission, kg;

A is ash content;

d_{fh} is dust ratio in ash;

η_{fh} is the efficiency of dust removal;

C_{fh} is combustible content in dust;

Ash content A can be chosen as 20%. The dust ratio in ash is determined by the combustion method, it ranges from 15% to 25% if it is chain furnace. The efficiency of dust removal η_{fh} can be 80% if it is cyclone dust removal. Combustible content C_{fh} ranges from 15% to 45% [46]. Assuming A=20%, $d_{fh} = 20\%$, $\eta_{fh} = 80\%$, $C_{fh} = 20\%$, the dust emission rate can be 10kg/t.

Other than SO_2, NO_x, CO_2 and dust, CO, coal ash, total suspended particulates and slag can be chosen as 0.26kg/t, 110kg/t, 0.4kg/t and 30kg/t [42] as listed in Table 3.

Pollutants	SO_2	NO_x	CO_2	CO	TSP	Coal Ash	Slag
Emission Rate(kg/t)	18	18.64	1731	0.26	0.4	110	30

Table 3: Pollutants Emitted from Coal Fire Plants

Source: Cheng and references cited in the above text.

Environmental cost of coal

The environmental value of SO_2 can be calculated from the cost of desulfurization. Zhang Jin et al. discussed three types of desulfurization: The calcium-sodium double alkali method; the limestone-gypsum wet desulfurization; and magnesium oxide wet desulfurization. There are two common types of coal tested. Coal 1# has high sulfur content and low heating value. Coal 2# has low sulfur content and high heating value. Coal 1# can generate SO_2 26.32kg/t, while coal 2# can generate SO_2 12.83kg/t. Taking the average value, the SO_2 emission rate could be 19.575kg/t, which is similar to the result calculated [47] as listed in Table 4.

Desulfurization Method	Cost for Coal 1#	Cost for Coal 2#
Gypsum desulfurization	149.90	100.84
Sodium desulfurization	267.19	158.01
Magnesium desulfurization	148.38	100.1

Table 4: The Cost of Desulfurization to Generate 1-ton Coal (yuan)

Source: Zhang, J. Liu, X. Feng, Z. et al. 2014. Cost of coal and desulfurization processes in different combinations for coal – burning boilers. Environment Protection Technology. 2014(2).

Calcium-sodium desulfurization method costs much more money per kg of sulfur than the other two methods. If choosing the average cost of these two types of coal, the lowest cost would be 124.24 yuan per 1-ton-coal.

The environmental value of NO_x is as high as 8000 yuan/t, as it is a main precursor causing photochemical smog. The greenhouse effect it causes is 200 to 300 times higher than CO_2. The environmental value of CO can be chosen as 1000 yuan/t [[48]].

There are no charges for the environmental value of CO_2 it in Sewage Charge Standard. There ought to be environmental value assessment for its influence in global warming. One environmental value of CO_2 is $20/ton internationally which is too high for China [[49]]. One way to assume CO_2 cost is to refer to the ratio of the environmental value [48] of SO_2 to CO_2 in United States, which is around 80 to 1. As the cost of desulfurization is 124.24 yuan per 1-ton-coal, which is 6902 yuan per ton, the cost of CO_2 would be 86 yuan/ton. If we refer to the ratio of the environmental value of NO_x to CO_2, which is 348.8:1, the environmental value of CO_2 would be 23 yuan/ton. If we refer to the ratio of the environmental value of CO to CO_2, which is 34.88:1, the environmental value of CO_2 would be 29 yuan per ton. Taking the average of these 3 values, this report assumes 46 yuan per ton as the environmental value of CO_2.

Referring to Sewage Charge Standard, solid waste and hazardous waste charges like total suspended particulates, coal ash and slag can be 2200 yuan/t, 120 yuan/t and 100 yuan/t respectively. Table 5 lists the environmental value of these pollutants.

Pollutants	Environmental Value (yuan/t)	Environmental Value per ton Coal (yuan)
SO_2	6902	124.24
NO_x	8000	149.12
CO_2	46	79.63
CO	1000	0.26
TSP	2200	0.88
Coal Ash	120	13.2
Slag	100	3

Table 5: The Environmental Value of Pollutants (yuan/t)

Source: Shan Cheng

The estimated total pollutant cost of 1 ton coal is 370.33 yuan. Considering the pollutants in the link of use accounts for 47.8% of the total environmental value, the total environmental value of wind power replacing coal fire plants would be 774.75 per ton coal. To generate 1-kWh electricity, 320 grams of standard coal need to be combusted, so the environmental value of wind replacing coal would be 0.25 yuan/kWh.

CONCLUSION

Wind integration causes many problems due to its geological limitations, the intermittency and the randomness of wind resource. In order to maintain the stability of wind power system, more reserve capacity is needed for any wind power project. Wind integration adds more cost into the total cost. However, the fuel for wind power is free to use and it does not generate any pollutants. So the cost saved by wind power can offset the pollution, environmental damage and health damage caused by coal.

Chapter 4: *Cost of a Wind Farm in Urumqi*

Urumqi is the capital of Xinjiang, which is located in northwest China. The wind resource in northwest China accounts for more than 50% of the total wind resource nationally. Dabancheng wind power station is the biggest wind farm in China. It is located on the way from Urumqi to Tulufan. In 2010, the population of Urumqi was 3 million. This large population implies a big demand for electricity. As Urumqi belongs to category I resource zone. the electricity price in this region will be 0.4yuan/kWh in 2018. The expected operation hours is 2500 hours, but the actual operation hours was 1500 hours in 2012[[50]]. The cost of a 50MW wind farm with a 20-year lifetime is used as an example.

Figure 15 [[51]] illustrates that the best potential wind source is in the winter. The average wind velocity at 10 m is 3.61 m/s, while the average wind velocity at 70m is 4.77 m/s. The greater the height, the faster the wind speed. We choose 1.5MW wind turbine for this wind farm. The height of a 1.5MW wind turbine is usually around 70 meters, so the data at 50m is transferred to 70m.

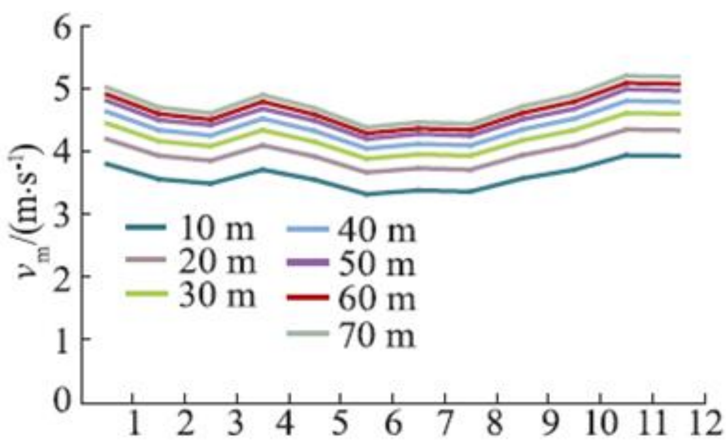


Figure 15: Monthly Mean Wind Speed at Various Altitudes in Typical Year in Urumqi.

Source: Stackhonse P W. 2014. Surface meteorology and solar energy. NASA. Houston, USA.

CAPACITY FACTOR

As discussed in Chapter 2, a consumption is that wind velocity follows Weibull distribution. With the estimated information provided by NASA [51], Table 6 illustrates wind velocity distribution in Urumqi at the height of 50m is taken.

average speed at 70m	1.15m/s	4.72m/s	8.92m/s	13.12m/s
speed at 50m	0-2m/s	3-6m/s	7-10m/s	11-14m/s
Jan	15	62	23	0
Feb	18	65	17	0
Mar	18	66	15	0
Apr	17	62	20	1
May	20	62	17	1
Jun	23	63	13	0
Jul	19	67	13	0
Aug	22	65	13	0
Sep	21	60	18	1
Oct	18	60	21	1
Nov	16	57	27	1
Dec	14	61	25	0

Table 6: Monthly Averaged Percent Of Time The Wind Speed At 70 m Above The Surface.

Source: Stackhonse P W. 2014. Surface meteorology and solar energy. NASA. Houston, USA.

Using equations (12) and (13), the shape parameter k=2.22, and the scale parameter c=5.54. So Weibull distribution can be expressed as:

$$f(V) = \left(\frac{2.22}{5.54}\right)\left(\frac{V_i}{5.54}\right)^{2.22-1} \exp\left[-\left(\frac{V_i}{5.54}\right)^{2.22}\right]$$

Figure 16 illustrates the distribution of wind velocity based on the Risk software within Excel.

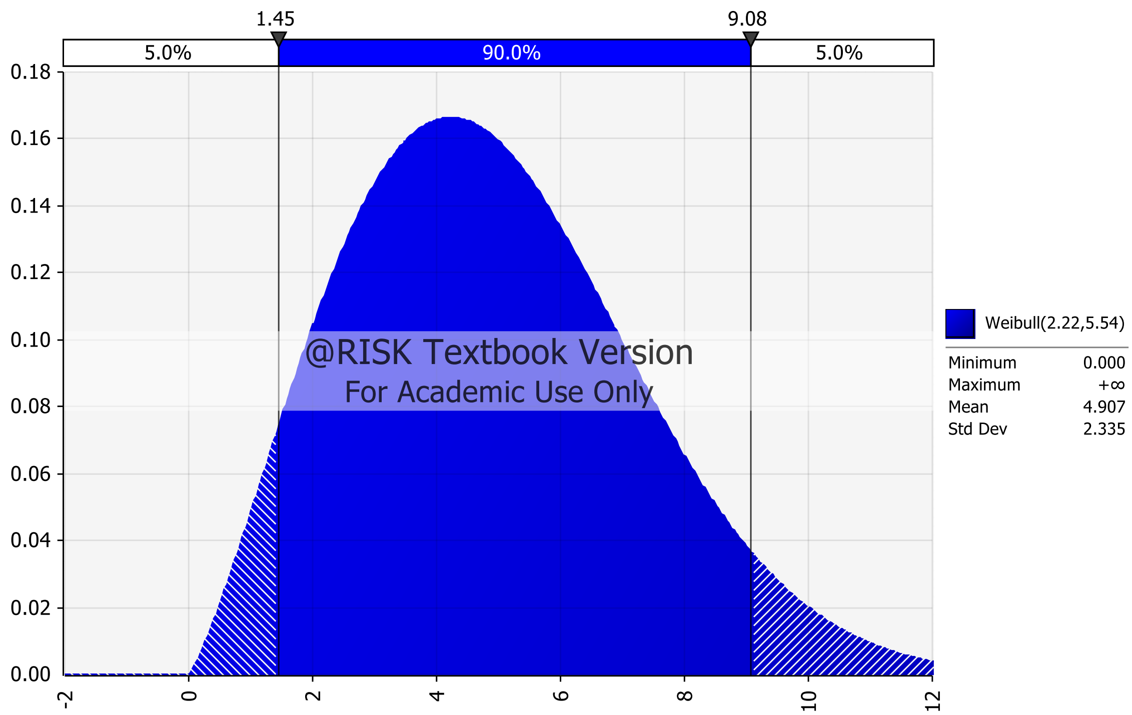


Figure 16: Weibull Distribution of Wind Speed at the Height of 70m in Urumqi (Cheng)

Assume the cut-in speed is 3.5m/s, the cut-out speed is 25m/s and the rate speed is 10m/s. Then the capacity factor will be 20% using equation (15):

$$\mathrm{CF} = \frac{e^{-(\frac{V_i}{c})^k} - e^{-(\frac{V_r}{c})^k}}{(\frac{V_r}{c})^k - (\frac{V_i}{c})^k} - e^{-\left(\frac{V_c}{c}\right)^k} = 20\%$$

Revenue

With a wind power price of 0.44 yuan/kwh, the effective hours, annual revenue and total revenue in 20 years can be derived using equation (18).

$$\text{Effective Hours} = 24\text{hours} \times 365\text{days} \times \mathrm{CF} = 1752\text{hours}$$

$$\text{Annual Revenue} = \text{Effective Hours} \times \text{Rate Power Output} \times \text{Electricity Price}$$

$$= 37.06 \text{ million yuan}$$

$$\text{Total Revenue} = \text{Annual Revenue} \times \text{Lifetime} = 741.2 \text{ million yuan}$$

INTEGRATION COST

There are no firm rules for reserve capacity of wind farm. Table 7 uses a reserve capacity accounts of 5% of the total capacity [52].

Reserve capacity rate	5%
Reserve capacity (MW)	2.5
Annual electricity generation by reserve capacity (MWh)	4380
Reserve capacity price (yuan/KWh)	0.112
Reserve capacity cost (million yuan)	0.49

Table 7: The Integration Cost of Wind Farm

Source: Ministry of Water Resources and Electric Power. 1981. Guideline for Power Systems. Beijing, China.

CAPITAL EXPENDITURE

Since 2007, the unit price of a standard 1.5 MW-sized wind turbine decreased from 6,700yuan/kW at the beginning of 2007, to 6,300 yuan/kW in 2008, and to 3200 yuan/kW in 2012. Empirical studies using learning curve models showed that the learning rate of wind turbine in the early period from 2003 to 2007 ranged around 4.1% to 4.3% annual reduction in cost, while in the more recent period from 2008 to 2013 it could be above 12% [53]. Assume that the decreasing learning rate is 6% from year 2012 to 2017, and the other investment components remain unchanged, so the total investment cost would be:

Cost Type	Cost
Wind turbine (yuan/KW)	2800
Wind turbine cost C_t (million yuan)	140
Wind farm construction cost C_i (million yuan)	42.5
Early stage and land cost C_l (million yuan)	28.5
Grid integration cost C_g (million yuan)	9.8
Total C_n	218.8

Table 8: The Total Capital Expenditure of Wind Farm [18]

Source: Liu, Z. Zhang, W. Zhao, C. etc. 2015. The Economics of Wind Power in China and Policy Implications. Energies 2015, 8, 1529-1546.

OPERATION AND MAINTENANCE EXPENDITURE

Spare Parts Cost

Table 9 lists spare parts cost.

Supplies	Cost (million yuan)	Remarks
Carbon Brush	0.01	Every 1 to 2 years
Filter	0.04	Every 1 to 2 years
Lubricating Oil	0.7	Every 3 to 5 years
Pitch Battery	0.4	Every 2 to 3 years
Others	0.5	Every year
Total OPEX	0.87	Every year

Table 9： The Spare Parts Cost of a Wind Farm [54]

Source: Zhang Guoyong. 2015. Analysis about the actual cost of wind turbine service, CNWEE. http://fd.bjx.com.cn/special/?id=674521.

Scheduled Maintenance

Table 10 lists the cost of scheduled maintenance.

OPEX Component		Cost (Million yuan)	
Employee	Manager	0.15	1 persons
	Technician	0.12	1 persons
	Engineer	0.07	3 persons
Vehicles		0.05	
Salary benefit		0.05	
Scheduled maintenance		0.3	
Insurance		0.53	
Total in 20 years		28.2	

Table 10： The Scheduled Maintenance Cost of a Wind Farm [54]

Source: Zhang Guoyong. 2015. Analysis about the actual cost of wind turbine service, CNWEE. http://fd.bjx.com.cn/special/?id=674521.

If include a half-million-yuan technical improvement cost each year, the average cost of total OPEX each year is going to be 2.25 million yuan..

FINANCIAL COST

Construction Interest

As the construction period for a wind farm is usually 1 year, the times calculating interest each year m=1, the annual interest rate R equals to the effective annual interest rate

R_i. The total interest generated by construction loan can be calculated using equal principal and interest method as in Table 11.

Loan (million yuan)	Annual interest rate	Loan period	Total construction interest (million yuan)
211	6.21%	10	78.5

Table 11: The Construction Interest of a Wind Farm

Source: Shan Cheng

Working capital interest

Table 12 lists the working capital interest. For a 50MW wind farm, the total working capital needed is 1.5 million yuan. As required, the initial working accounts for 30% of the total working capital, which is 0.45 million yuan. The rest 1.05 million yuan was borrowed from the bank.

Working capital and its interest	cost
Unit working capital (yuan/KW)	30
Total working capital (million yuan)	1.5
Initial working capital (million yuan)	0.45
Loan (million yuan)	1.05
Loan period (year)	10
Annual interest rate	6.21%
Total interest (million yuan)	0.39

Table 12: The Working Capital Interest of a Wind Farm

Source: Shan Cheng

As a result, the total financial cost is:

$$FIN_n = A_w + \sum_{n=1}^{N} l_n + \sum_{n=1}^{N} s_n = 80.39 \text{ Million yuan}$$

TAX

Using equations (29) to (33), taxes can be calculated as listed in Table 13

Tax type	Tax every year (million yuan)	
Value added tax	034	1st to 10th year
	2.53	10th to 20th year
Income tax	0	1st to 3rd year
	2.625	4th to 6th year
	5.25	7th to 20th year
Sales tax and additional tax	0.0	1st to 10th year
	0.46	10th to 20th year
Property tax	0.012	
Land use tax	5	2500000 m^2
Total tax for 20 years	125.22	

Table 13: The Tax of a Wind Farm (Cheng)

ENVIRONMENTAL VALUE

As discussed in Chapter 3, the environmental value would be 0.25 yuan/kWh, so the environmental value for this wind farm is:

$$\text{Total enironmtal value} = \frac{0.25\text{yuan}}{\text{kWh}} \times \text{Effective hours} \times \text{Rated power output}$$

$$= 21 \text{ million yuan}$$

THE LEVELIZED COST OF ELECTRICITY

The own usage ratio in a typical wind farm equipped with automatic generation control and other reactive power compensation and harmonic suppression devices is 2%. This means that the wind farm will consume 2% of its power generation for operating itself. The discount rate reflects the risk-adjusted opportunity-cost of capital. The minimum internal return rate requirement of power projects in China can be used as the discount rate, which is 8% [[55]]. LCOE can be calculated using equation (5).

$$LCOE = \sum_{n=0}^{N} \frac{CAPEX_n + OPEX_n + FIN_n + TAX_n}{(1+r)^n} \bigg/ \sum_{n=0}^{N} \frac{(C \times H \times (1-o_u))_n}{(1+r)^n}$$

$$= \sum_{n=0}^{N} \frac{repayment_n + OPEX_n + FIN_n + TAX_n}{(1+r)^n} \bigg/ \sum_{n=0}^{N} \frac{(C \times H \times (1-o_u))_n}{(1+r)^n}$$

$$= 0.33 yuan/kWh$$

CONCLUSION

The 0.33 yuan/kWh is 0.11 yuan/kwh lower than wind power price in Urumqi area. It means that this approach is feasible and this project is profitable. If taking concern of the 0.25yuan/kWh environmental value, the actual electricity cost of this wind farm is 0.08 yuan/kwh. The coal electricity price in Xinjiang is 0.29 yuan/kwh which is far lower than the 0.44 yuan/kwh wind electricity. If the environmental value can be reflected in its costs. Wind power is even cheaper than coal power price.

Chapter 5: *Conclusion*

Wind energy is one of the most abundant renewable energy. It can produce large-scale electricity for urban area as well as support electricity independency in remote area. It rarely generate pollution, except for the pollution during wind turbine production and the pollution generated by thermal units of reserve capacity. Wind can play a more important role if it is cost-effective compared to other source.

Wind power cost reflect local wind energy resource and its cost. Wind turbine cost with its capacity factor can influence the profit of a wind farm. The more the wind turbine runs in a day, the lower the cost per kilowatt is. Wind farm can be built in area where there is high wind velocity and wind energy density to improve capacity factor. Selected wind turbines can match the local wind resource based on the parameters of the wind turbine and wind velocity at a corresponding height. One way to reduce wind power cost, is to reduce wind turbine cost, as wind turbine cost accounts for 70% to 80% of the total investment cost. As China produces wind turbines at a lower cost among some other countries, it is better for China to use wind turbines produced locally and improve wind turbine technology at the same time to lower the costs. Reserve capacity is necessary for a wind farm due to the intermittency and randomness of wind resource. The optimization of reserve capacity can minimize reserve capacity cost. Compared to fossil fuels, wind power can produce more environmental benefits. Taking account of its environmental value can not only improve the value that wind power can offer, but can also lower its cost so that it can compete with conventional thermal fire plants.

With all analysis mentioned above, here are the conclusions:

1. Using the methods in this paper, we can successfully derive the levelized cost of wind power. Compared to coal price, the derived cost is still too high. In

northeast and northwest China where there is abundant wind energy resource, there is also abundant coal, natural gas and petroleum. For now, the wind power price cannot compete with the fossil fuels there. Plus, area with these ample energy resource, has relatively small population and is far from population center. It makes it harder to develop large-scale wind power project.

2. In the example of wind farm in Urumqi, the annual income is 37 million yuan while the annual debt needs to be paid is 30 million yuan. Plus O&M cost and tax, the wind farm starts to make actual profit after all the loan is paid. As a result, government should provide enough subsidies in the first few years to keep wind farms operating. However, this year Chinese government promoted green credits trading. This implies that it is going to reduce the subsidies gradually. For now, we could only hope trading green credits can help improving the income of wind farms.
3. There is still space to lower wind power cost. As wind turbine cost is decreasing each year, grid infrastructure is getting more and more mature, energy storage technologies are under developing, wind power cost can be lowered in various ways. Most importantly, environmental value can reduce wind power cost significantly as long as the environmental issue and health issue caused by coal get enough attention

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